National Aeronautics and
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The Stratospheric Aerosol and Gas Experiment IV

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What is SAGE IV?

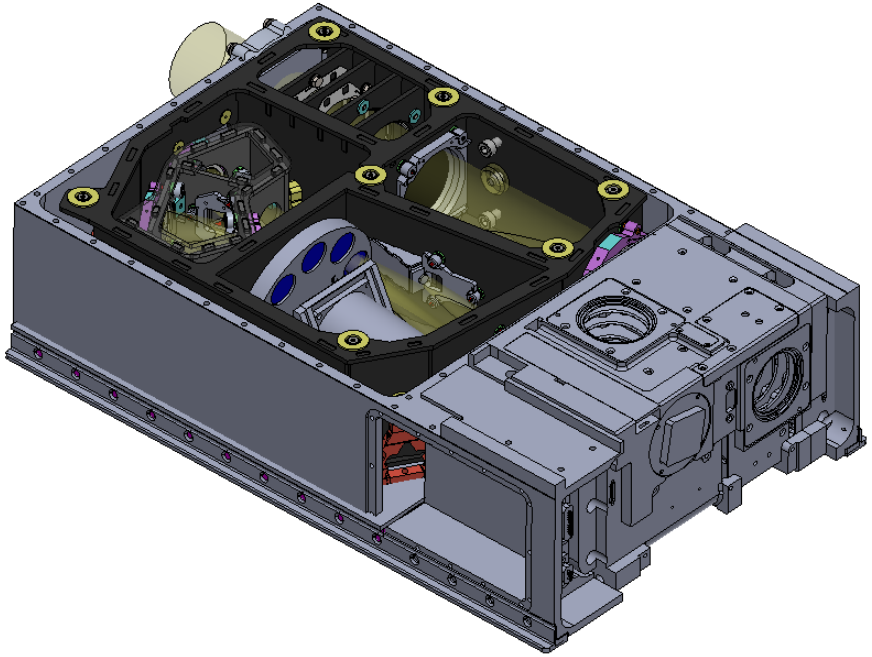
- SAGE IV is a climate continuity mission concept focused on key trace gas constituents in the stratosphere and upper troposphere
- Utilizes the observation method of solar occultation
  - High vertical resolution measurements with semi-global coverage at monthly time scales, which is sufficient for most stratospheric processes
  - Provides a calibration/validation standard for concurrent, less precise, less stable, high-density samplers to ensure proper continuity of the measurement system ensemble over time
- New imaging technique simplifies the observation, significantly reducing pointing requirements and thus instrument complexity, size, and cost
- Enables cost-effective sustainability of measurements
- Small constellation (3 or 4) can enable coverage at weekly time scales

Why Imaging?

Challenges with Scanning	Benefits of Imaging
When using a scanning spectrometer, pointing knowledge becomes critical and subsequently requires heavy (~350 kg) and expensive mechanisms	Absolute pointing is intrinsic to solar imaging
Assumptions must be made about the instrument's mechanical stability during an event. • Linearity of scan mirror motion • Azimuthal tracking expects a uniform image • Non-orthogonal transient behaviors	No assumptions are required for tracking mechanisms as all that is needed is to keep the full solar disk inside the field of view (though not necessarily centered)
External meteorological data are required to compute refraction for tropospheric and lower stratospheric pointing	Atmospheric refraction is independently retrievable
Radiometric symmetry of the solar disk must be assumed	Anisotropy of the solar disk (e.g., sunspots and granularity) is measured

1^{st} Gen. Concept: SAGE Follow-on

- ESTO-Funded IIP: SAGE IV Vis/NIR instrument to continue SAGE science goals
- Solar occultation imager capable of meeting or exceeding SAGE-quality ozone, aerosol, and water vapor measurements
- Instrument and spacecraft small enough to fit in a 6U CubeSat form factor for a significant size and cost reduction (~1/10th)
- Accelerated schedule that ensures measurement validation by operating concurrently with SAGE III
- Simple design offers extensibility for greater utility:
  - Constellation for better coverage
  - IR extensibility for new target species
  - Expansion to 12U to include spectrometer
  - Potential inclusion of limb scatter mode
  - Solar occultation at Venus or Mars



SAGE IV Science

Ozone Concentration:

- Precision (≤1%) and vertical resolution (≤1 km) required for trend assessments
- Necessary stability derives from measurement technique and on-board instrument characterization (SAGE II was ≤2%/dec)

Aerosol Extinction:

- Unique data product intrinsic to solar occultation that does not require modeling of particle size or type
- Precision (≤5%) and vertical resolution (≤1 km) same as previous SAGE instruments (exceeds other non-SAGE instruments)
- Multi-wavelength measurements can be used to infer aerosol properties (e.g., size and type) and can improve other instrument retrievals (e.g., limb scatter/emission)

Water Vapor & NO2 Concentrations:

- Precision (≤10–20%) and vertical resolution (≤2 km) same as previous SAGE instruments

Neutral Density / Temperature:

- Imaging offers intrinsic measurement of refraction and inference of neutral density and temperature

Spectral Channel	Target
Light Block	Dark Current
Diffuser	Flat-Fielding
448 ± 1 nm	NO2 / Aerosol
452 ± 1 nm	NO2 / Aerosol
525 ± 5 nm	Aerosol
600 ± 10 nm	Ozone
676 ± 5 nm	Aerosol
945 ± 15 nm	Water Vapor
1020 ± 10 nm	Aerosol
Possible Additions	**Purpose**
Split H2O into 2	Better Water Vapor
756 / 868 nm	Better Aerosol
385 nm	Density in Mid-Atm.
O2 A-band	Better Dens/Temp

SAGE IV Pathfinder Instrument Design

Telescope:

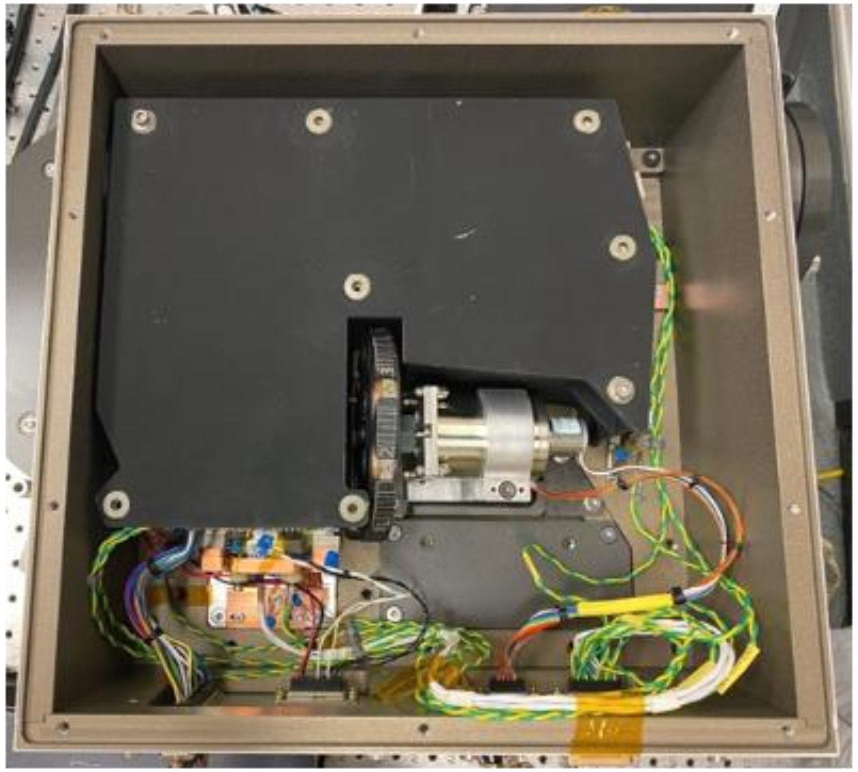
- Compact (<20x20x10cm), state-of-the art fabrication
- Excellent stray light mitigation demonstrated by testing at SDL
- Low- and matched-CTE materials meet requirements over potential CubeSat temperature ranges

Detector:

- 2D array for instantaneous spatial imaging
- Deep-well photodiode array for high-SNR in shot noise regime
- Silicon spectral range (UV/Vis/NIR) for low dark noise and simple temperature control (i.e., TEC instead of cryo-cooling)

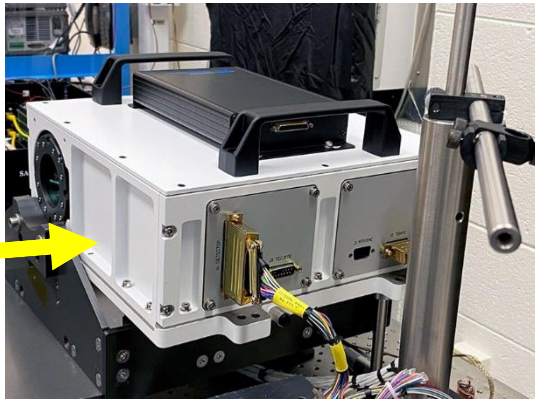
Filter Wheel:

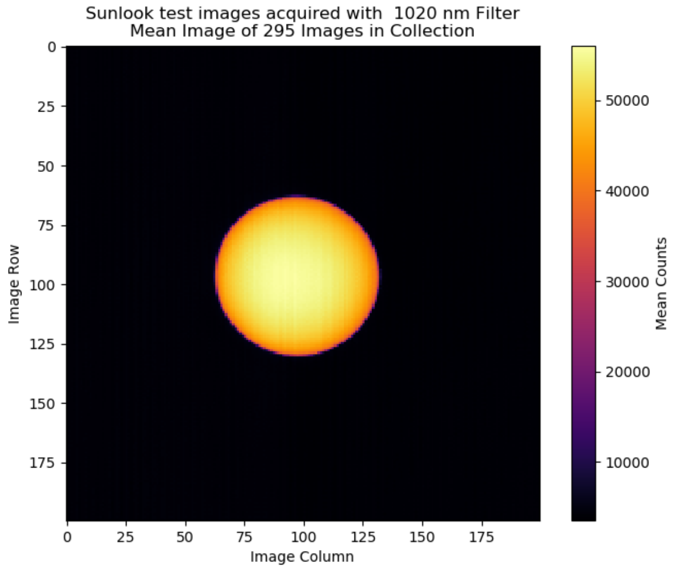
- Contains 7 science channels (similar to SAGE II)
- Enables on-orbit characterization during active science events
- Low motor speed / torque required (30 rpm)



Instrument Testing

- SAGE IV prototype integrated into surrogate chassis for testing.
- Extensive system testing and characterization performed in laboratory clean room with calibrated light source.
- Sunlook testing occurred outdoors with instrument surrogate chassis positioned on equatorial mount.
- Closed-loop control of the system maintained the Sun in the instrument FOV.
- Laboratory and Sunlook testing successfully assessed the integrated system performance.





SAGE IV Status

- The SAGE IV “Viz” concept was essentially “shovel-ready” in 2020
- Would deliver EDU and flight instrument yielding SAGE solar occultation science at low cost and short development time
- As a continuity mission, there are no NASA AOs to propose to
  - EVI/EVM require a specific, short-term science focus
  - Aerosol, ozone, and water vapor may be too narrow for EVC-2
- As it pertains to ozone and aerosol continuity, OMPS-LP (SNPP [2011], JPSS-2 [2022], JPSS-3 [2027]) and SAGE III (ISS [2017]) are carrying the record along for the near future with ALTIUS also launching soon [2025/6]

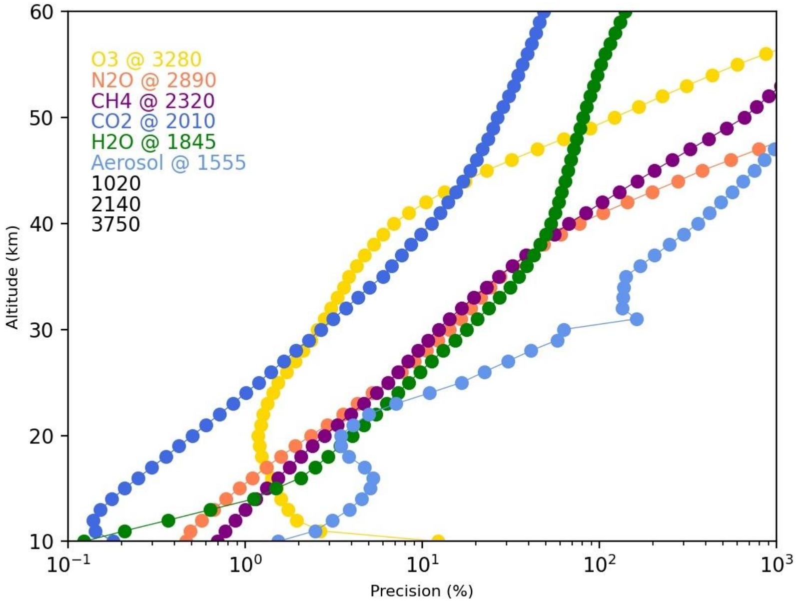
- Explore extensibility options!

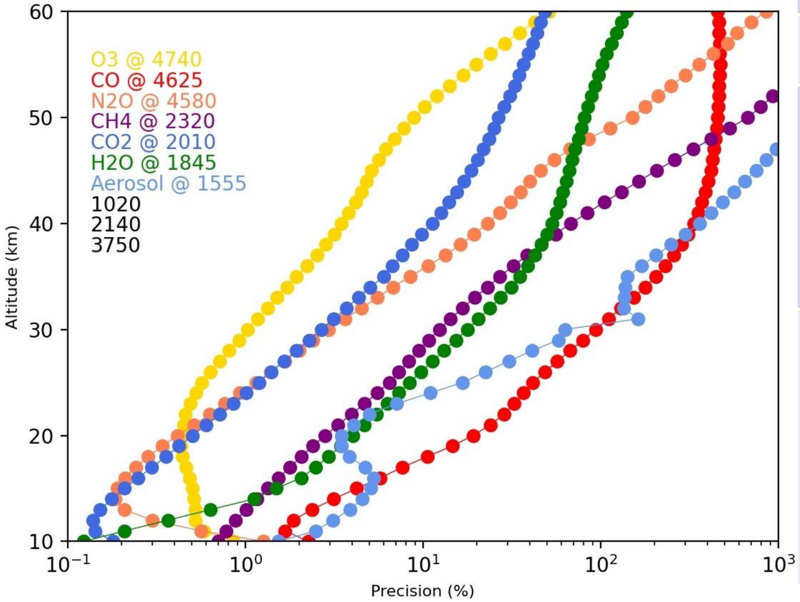
2^{nd} Gen. Concept: SAGE IV IR

- Implement extensibility of “Viz” instrument to enable observations in the infrared
- IR measurements (1–4 um or 1–5 um) enable enhanced science
  - Similar O_3 and aerosol quality as “Viz”
  - 10x better H_2O measurements than “Viz”
  - Add CH_4, CO_2, N_2O, and CO (5 um version)
  - Can start to differentiate aerosol composition
- New species and spectral regime are beyond the heritage of previous SAGE measurements
  - New modeling to optimize channel locations and determine error budget
  - New engineering challenges to consider

SAGE IV IR: Science Modeling

- For broadband radiometry, there are several possible channel choices for each species of interest
- Optimized channel choice (both general location and specific bandpass) to maximize precision and minimize biases to bandpass knowledge and interference from other species

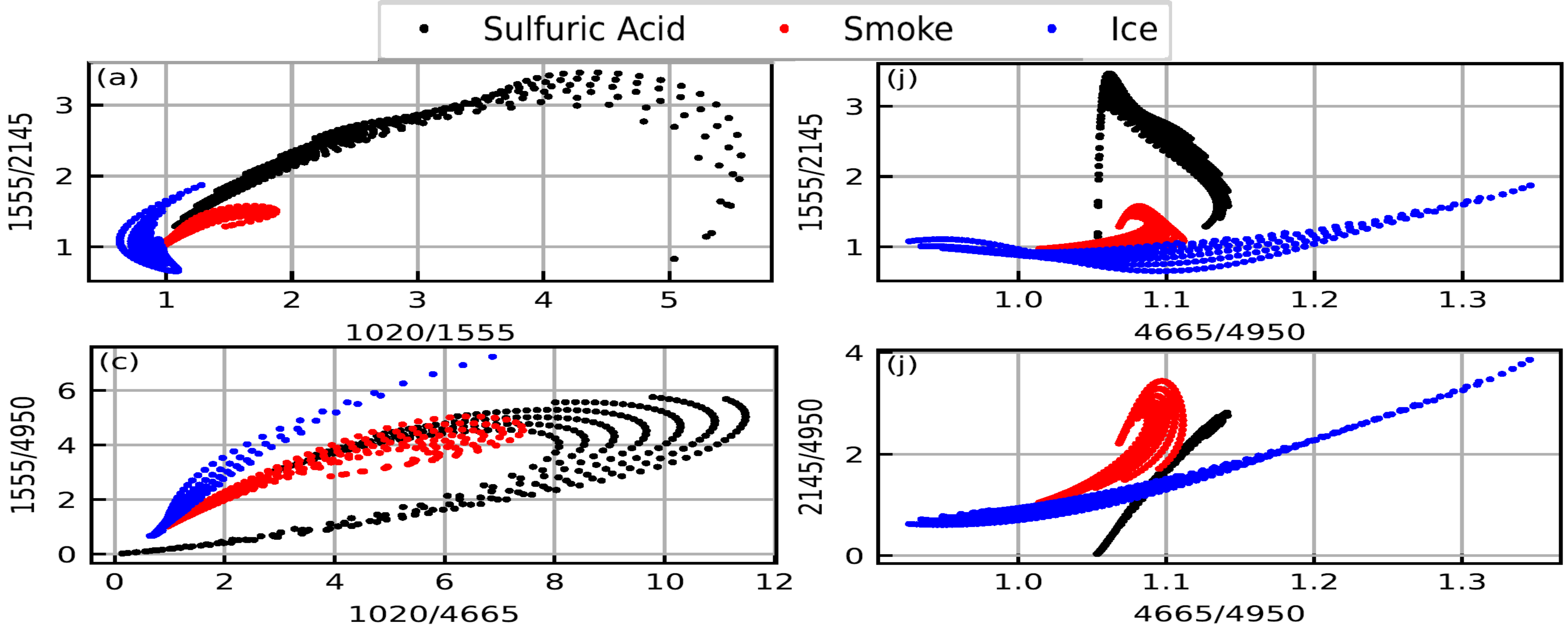




Spectral Channel	Target
Light Block	Dark Measurement
Diffuser	Flat-Fielding
1020 (10nm FWHM)	Aerosol
1555 (15nm FWHM)	Aerosol
1850 (35nm FWHM)	Water Vapor
2010 (15nm FWHM)	Carbon Dioxide
2135 (10nm FWHM)	Aerosol
2315 (20nm FWHM)	Methane
4 um Version: 2885 (40nm FWHM) 3285 (35nm FWHM) 3 Aerosol Channels	 Nitrous Oxide Ozone Aerosol
5 um Version: 4550 (50nm FWHM) 4625 (75nm FWHM) 4725 (75nm FWHM) 2 Aerosol Channels	 Nitrous Oxide Carbon Monoxide Ozone Aerosol

SAGE IV IR: Aerosol Modeling

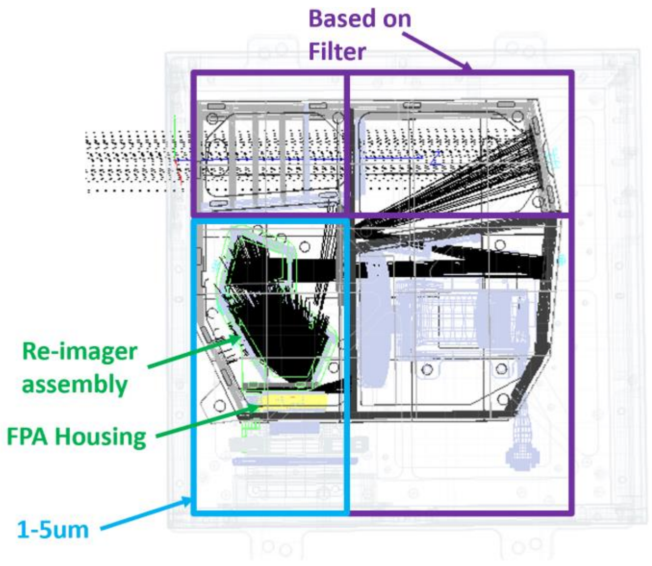
- Aerosol modeling shows how IR channels enable differentiation of not only particle sizes but also composition



SAGE IV IR: Hardware Changes

- Necessary Changes from Vis/NIR instrument:
  - Change detector from Silicon to MCT – Same family from same manufacturer
  - Encase detector in a cold chamber – Simple design modification
  - Cryocool detector and cold chamber – Small form-factor cryocoolers available
  - Larger volume required for cooling hardware – Commercial 12U CubeSat
  - Different science channels – Simple purchase from filter vendors
- Thermal emission from internal hardware, optics in particular, creates additional source of noise and/or bias
  - How much bias and/or noise is created?
  - Is cooling the optics required?
  - Is a cold window required?

SAGE IV IR: Thermal Optical Modeling



- MCT spectral sensitivity can be strongly restricted (1–5 um)
- Thermal Self Emission (TSE) contribution
  - Front-end Optics "Beam Reducer"
  - Back-end Optics "Reimager"
- Beam Reducer
  - Only TSE within a filter bandwidth makes it to detector
  - Cannot* be measured during occultations so acts as a source of bias
  - Ratio of TSE to solar flux is the quantity of interest
- Reimager
  - TSE across full detector spectral sensitivity makes it to detector
  - Will be measured during occultations so acts as an offset and noise source
  - TSE as a fraction of pixel well capacity is the quantity of interest

SAGE IV IR: TSE Modeling Results

- In general, the “4 um” version leaves little to be concerned about
- TSE from the Reimager is 1–2 orders of magnitude larger than from the Telescope (at long wavelengths) yet of less concern because of active characterization
- No cold window
  - Reimager TSE noise is large but manageable, with SNRs ~ SAGE III/ISS
  - Telescope TSE bias* is too large at longer wavelengths ($\sigma_{SYS} \sim 25\times\sigma_{RAND}$)
- Cold window (e.g., ND2)
  - Reimager TSE scales with OD to negligible levels
  - Telescope TSE scales with OD to manageable levels ($\sigma_{SYS} \sim \sigma_{RAND}$ / 10)
  - Baffle/detector housing temperature sets noise floor
- Self-characterization and simple design addition mitigate impact of TSE

SAGE IV IR: Self-Characterization

- Solar occultation technique is “self-calibrating” from orbit-to-orbit and month-to-month, but not over the few minutes of each observation
- SAGE IV is designed with “active” characterization in mind (i.e., characterization of instrument performance throughout the active science mode)
    - Dark current and Reimager TSE via light block (0.5 Hz, channel independence)
    - Beam Reducer TSE via image outskirts (0.5 Hz, each channel)
    - Pixel-to-pixel cross-calibration via diffuser (0.5 Hz over exoatmospheric range)
    - Other thermal transient behaviors via analysis over exoatmospheric range
- Special characterization events are also planned to improve calibration of images
    - Dark current trending
    - Beam Reducer TSE temperature dependence
    - Special flat-fielding “scans” to analyze diffuser performance/sensitivities

SAGE IV IR Status

- SAGE IV IR offers a sustainable solution for climate continuity observations
    - Ozone layer
    - Greenhouse gases
    - Aerosols and properties to observe volcanic and wildfire events
- SAGE IV will offer a calibration-quality reference standard for future missions
- Instrument design is mature, with only minor engineering analyses remaining
- SAGE team is actively soliciting science co-investigators (contact us if interested!)
- Concept is amenable to upcoming AOs (e.g., EVC-2)